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Strength regain in soil aggregate beds by swelling and shrinkage**

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A b s t r a c t. Strength regain in aggregate beds as a consequence of wetting and drying cycles was studied in two Andisols and one Mollisol from Chile, collected at two depths (0-10 and 40-60 cm). In the Mollisol, wetting and drying cycles promoted an increase of mechanical parameters (cohesion and precompression stress value), associated with increase of bulk density. The Andisols showed the same tendency, but in some coarse aggregate beds the measured values decreased or remained constant. After six cycles of wetting and drying, the restructuring of the aggregate beds from the Mollisol resembled more the measured properties of non-disturbed samples than the identically prepared samples from the Andisols. The change of pore water pressure during mechanical tests depends on the soil development: the Mollisol is sensitive to external load, during compression and shear tests the pore water pressure changed intensely, while in the younger Andisol, irrespective of the stress applied, the pore water pressure did not change significantly. It is possible to find a strength regain in natural aggregate beds, but further investigations are necessary to understand the processes of pore formation and functioning in Andisols and their role in the pore water pressure behaviour.

K e y w o r d s: precompression stress, cohesion, angle of friction, soil structure, bulk density

INTRODUCTION

Aggregate formation in soils containing more than 12% clay usually occurs when they shrink and swell (Horn and Smucker, 2005). This process results in stabilization with time, which does not only create secondary inter-aggregate pores but also more rigid aggregates. The more often the swelling and shrinkage occurs the better the particle arrangement becomes and the stronger the total structure system gets. The latter one is also known as age hardening, curing or strength regain (Błażejczak *et al.*, 1995). The main mechanisms of strength regain are the rearrangement of soil particles into positions of minimum free energy and the chemical cementation at the contact area of particles. Furthermore, biological activity results in the formation of more stable soil aggregates (Chaney and Swift, 1986), which together with the age hardening produces an aggregate strength increase.

Soil strengths depend on grain size distribution, kind and size of clay minerals, type and amount of adsorbed cations, content and kind of organic substances, water suction, effect of swelling and shrinkage, and of biological activity (Barzegar *et al.*, 1995a). Wetting and drying cycles increase the aggregate bulk density of remoulded soils and increase the tensile strength of the aggregates (Horn *et al.*, 1994). This increment depends on soil texture, being more effective in a clayey soil than in a silty loam soil (Zhang *et al.*, 1997). On the other hand, the increase of aggregate bulk density depends on the drying intensity and the number of drying events too: the wetter the soil was kept and the larger the number of cycles, the higher the increase. Nevertheless, Barzegar *et al.* (1995b) showed that in mixtures of particle sizes, the wetting and drying processes can also promote a decrease of tensile strength after compaction, if due to changes in the pore water pressure. During the compression test the menisci forces get reduced and the rearrangement of particles results in the formation of a weaker configuration.

In natural aggregate beds, a single cycle of wetting and drying increased the cone penetration resistance, soil cohesion, adhesion and internal friction, while the aggregate mechanical stability, evaluated by a soil drop test method, decreased. Ghezzehei and Or (2003) proposed that the two

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main components that determine the structural dynamics of aggregated soils are the geometry and spatial arrangement of soil aggregates, and the intrinsic properties of the aggregate-forming soil. The spatial arrangement determines the pore functionality, because any external load collapses the coarse porosity and affects the pore continuity, decreasing the gas and water fluxes (Horn, 2003) and increasing the tensile strength (Munkholm *et al*, 2002). The intrinsic properties of the soil determine the ability to withstand external mechanical loading, but during this event the soil strength can increase or decrease, depending on the behaviour of the X factor in the effective stress equation.

When soil is loaded, the voids ratio decreases approximately linearly with the logarithm of the normal load applied. Soil samples are the more compressible the lower the bulk density; nevertheless, the precompression stress value depends not only on the maximum pre-desiccation, but also on the hydraulic properties of the soil. The smaller the water flux and pore continuity, the more stable are the soils. On the other hand, the time dependency determines that the higher the stress application time, the smaller the precompression stress value becomes. The water suction of the initial unsaturated condition can change to positive pore water pressure values at normal stresses smaller than the precompression stress (Fazekas and Horn, 2005).

In shearing tests, within 0-500 kPa suction range, the shear strength increases linearly under low confining pressures, but this is not true in granular soils for the same suction range (Eko, 2005). The vertical displacement during the shearing test depends on the bulk density, but in general in loose soils there is a decrease of the sample height. For drained tests of non-saturated soil samples, the pore water pressure initially decreases by a diameter reduction of the air-filled pores *ie* the soil sample gets drier at the same water content, but increases if there are no more air-filled pores or if the drainage of excess water in water-filled pores is prevented by non-continuous pores. The effect of water pressure/suction on effective stress depends, therefore, on the normal load applied. The critical normal stress is lower in shearing tests than in compression tests, because in the former the drainage of excess water is much more prevented due to complete disturbance of the pore system linked to a more intense soil compression. In this way the pore water pressure can also reach positive values (Seguel and Horn, 2005a).

The effective stress theory applied to unsaturated soil behaviour has been studied, contrasting non-disturbed and remoulded soils, placing special interest on the new cracks and the individual aggregates formed. Any increase in soil strength depends on the strength of the contact area between aggregates and inside aggregates between single particles, and can be linked with a reformation of also the menisci forces in between both components. Therefore, any soil volume change during swelling and shrinkage processes must also include such interactions between single particles or between aggregates and may result in stronger soil systems.

The aim of this study was to evaluate the strength regain in natural aggregate beds of two contrasting aggregate sizes, as a consequence of wetting and drying cycles, evaluating the soil behaviour dependency on the pore water pressure changes during mechanical tests.

MATERIALS AND METHODS

Soil samples at a depth of 0-10 and 40-60 cm were collected in three soils under grassland in the central valley of Chile (Table 1). The parent material is homogeneous, but due to different pedogenetic processes, the structure formation is very different. While the topsoil is well structured (strong, fine to medium, granular aggregates) in response to higher number and intensity of wetting and drying cycles, the deeper soil horizons are less developed (cohesive to weak, medium, sub-angular blocky). According to the USDA classification (Soil Survey Staff, 2003), the Osorno

T a b l e 1. Soil taxonomy classification and some important properties of the investigated soils

Serie	Soil taxonomy[1]	Depth (cm)	Bulk density (Mg m^{-3})	$C_{org.}$ [2] (%)	Clay[2] <2 μm (%)	Silt[2] <60 μm (%)
Graneros	Aquic Haploxeroll (Mollisol)	0-15	1.32	2.04	18.6	41.0
		40-60	1.52	0.66	12.9	32.9
Osorno	Typic Hapludand (Andisol)	0-15	0.99	5.58	23.9	31.6
		40-60	0.75	2.44	15.9	31.6
Pemehue	Pachic Fulvudand (Andisol)	0-15	0.69	9.30	22.5[3]	67.3[3]
		40-60	0.41	5.58	27.7[3]	59.9[3]

[1]Soil Survey Staff (2003), [2]CIREN (1996, 2003), [3]Mella and Khüne (1985).

soil (latitude: 40° 60´S) is an Andisol, representative for volcanic ash soils from south Chile, while the Pemehue soil (latitude: 38° 80´S) is a very young Andisol, very friable at the surface, while soft and loose in deeper horizons, both dominated by allophane and other randomly interstratified minerals. In contrast, the Graneros soil (latitude: 34° 50´S) is a Mollisol which was selected as it contains 2:1 minerals (vermiculite) and has been managed for several decades. The rainy weather and the lateral water flow in Andisols give them a highly wet condition in sub-superficial horizons, which persists because of the low number and low intensity of drying cycles.

Macro aggregates were gently crushed and separated by sieving at field water content. Two ranges of aggregate sizes were selected: 0.63-2 and 2-6.3 mm in diameter. These sizes tend to separate aggregates that have significantly higher strength and/or density than the soil matrix, and aggregates whose properties are similar to the soil matrix properties. Aggregate beds were prepared in cylinders of 10 cm in diameter and 3 cm in height, being filled manually. A standardized low pressure was applied to obtain identical bulk density values. To each range of size and depth, one or six cycles of wetting and drying were applied from 0 to -60 hPa. Aggregate beds had six replicates for each soil, depth, aggregate size and number of cycles.

After the wetting and drying cycles, bulk density of aggregate beds was measured. Samples equilibrated at a water pressure of -60 hPa were loaded in a confined, drained, compression test with time intervals between loads of 10 minimum and maximum normal stress of 400 kPa. The vertical deformation and the changes in pore water pressure at each given normal stress were recorded. Based on the measurements data of deformation as a function of normal stress, the precompression stress value was determined after Casagrande method (Baumgartl and Horn,1999). The shear test was performed as a strain-controlled test, with normal stresses between 13 and 400 kPa. For normal stresses lower than 100 kPa, new aggregate beds (not previously consolidated) were used, while for normal stresses higher than 100 kPa, samples from compression test, reequilibrated to -60 hPa, were used. The shear test was performed at a constant speed of 0.2 mm min^{-1}. The vertical deformation, the pore water pressure, and the shear strength were recorded, which results in the Mohr Coulomb failure line including the cohesion and angle of friction values (Fredlund and Rahardjo, 1993).

The pore water pressure during the compression and shear tests was measured with a micro-tensiometer inserted inside the aggregate bed. The sensor has a high resolution and sensitivity to pore water pressure changes with mechanical and hydraulic stresses applied, being previously used in other studies (Fazekas and Horn, 2005; Seguel and Horn, 2005a). The rates of change of pore water pressure during the shear tests were calculated as a function of time, depending on the normal load applied.

To compare the measured soil properties among the soil depths, number of cycles and aggregate size, analysis of variance (LSD, $P \leq 0.05$) was performed. For the Coulomb failure line and for the rate of change of pore water pressure, a linear regression analysis and the statistical significance (LSD, $P \leq 0.05$) were evaluated. The cohesion and the angle of friction were compared between the number of cycles, performing a comparison of intercepts and slopes by a t test with $P \leq 0.1$.

RESULTS

The mechanical properties: cohesion, angle of friction and precompression stress values of the undisturbed original soil samples are presented in Table 2.

The decrease of the cohesion values at 40-60 cm depth in Andisols is normal for these soils, especially under non-disturbed, *ie* natural conditions, because they maintain their original wetness and looseness linked with a low drying intensity. However, the precompression stress values either increased or did not change significantly with depth, because of the roughness and the shape of volcanic ash

Table 2. Some mechanical properties of original samples

Soil	Depth (cm)	Cohesion (kPa)	Angle of friction (°)	R*	Precompression stress (kPa)
Graneros	0-10	18.7	25.3	0.9993	23 a
(Haploxeroll)	40-60	23.1	20.2	0.9766	45 b
Osorno	0-10	16.1	38.7	0.9524	49 a
(Hapludand)	40-60	3.0	36.3	0.9604	79 b
Pemehue	0-10	27.2	27.5	0.9968	57 a
(Fulvudand)	40-60	14.0	29.2	0.9984	48 a

*values of Coulomb failure lines ($P \leq 0.05$); a, b – significantly different between depths.

particles which themselves are very rigid, like a sandy material (Ellies *et al.*, 2000). This condition could prevent particle rearrangement by wetting and drying in the aggregate beds, depending on the percentage of volcanic ash and the intensity of use. More detailed analysis of these mechanical properties will be presented in Seguel and Horn (2005b).

The values of bulk density of the aggregate beds after 1 or 6 cycles of wetting and drying are presented in Table 3. After one drying cycle, no differences between aggregate beds of different sizes could be detected. However, there were differences between depths: in both Andisols (Osorno, Pemehue), the deeper horizons presented lower values of bulk density, while the opposite was true in the Haploxeroll (Graneros), which can be also related with the bulk density of individual aggregates and the natural distribution of bulk density with depth (Table 1).

In the Graneros soil, there was a significant bulk density increase after six cycles of wetting and drying, but it did not reach the values of the undisturbed soil samples under in situ conditions (Table 3 *versus* Table 1). The highest increases were noted in superficial soil beds that resulted in even higher values than the sub-superficial soil beds. In both Andisols, the behaviour was different: Osorno soil presented a significant increase in the bulk density of the aggregate beds from 40-60 cm, whereas Pemehue soil had a significant increase in fine aggregate beds (0.63-2 mm) at both depths. Only the 40-60 cm layer of fine aggregate beds from Osorno soil reached values close to the natural soil conditions (Tables 1 and 3).

The generalized increments of bulk density of the aggregate beds should result in higher values of mechanical parameters after the six cycles of wetting and drying. The results of the precompression stress values are presented in Table 4.

T a b l e 3. Bulk density (Mg m^{-3}) of aggregate beds after 1 or 6 wetting and drying cycles

Soil	Depth (cm)	Aggregate size (mm)	1 cycle (Mg m^{-3})			6 cycles (Mg m^{-3})		
Graneros (Haploxeroll)	0-10	<2	0.804	a	A	1.209	a	B
		>2	0.844	a	A	1.070	b	B
	40-60	<2	0.901	b	A	0.996	c	B
		>2	0.929	b	A	0.978	c	B
Osorno (Hapludand)	0-10	<2	0.673	a	A	0.673	a	A
		>2	0.664	a	A	0.661	a	A
	40-60	<2	0.633	b	A	0.744	c	B
		>2	0.640	b	A	0.714	b	B
Pemehue (Fulvudand)	0-10	<2	0.435	a	A	0.496	a	B
		>2	0.445	a	A	0.446	b	A
	40-60	<2	0.331	b	A	0.376	c	B
		>2	0.333	b	A	0.336	d	A

a, b, c – significantly different in the column; A, B – significantly different in the row (LSD, P≤0.05).

T a b l e 4. Precompression stress values (kPa) of aggregate beds after 1 or 6 cycles of wetting and drying

Depth (cm)	Aggregate size (mm)	Graneros (Haploxeroll)		Osorno (Hapludand)		Pemehue (Fulvudand)	
		1 cycle	6 cycles	1 cycle	6 cycles	1 cycle	6 cycles
		(kPa)					
0-10	<2	7.3 A	14.3 A	12.5 A	17.8 B	13.2 A	19.5 B
	>2	5.6 A	6.7 A	15.3 A	14.3 A	16.5 A	10.8 B
40-60	<2	3.0 A	5.1 B	13.5 A	12.0 A	22.0 A	25.5 A
	>2	4.0 A	6.4 B	15.0 A	18.5 A	9.0 A	11.8 A

A, B – significantly different between number of cycles (LSD, P≤0.05).

There is a slight increase of the precompression stress values, but changes are not always significant. Only the coarse aggregate beds (>2 mm) from the superficial horizon of the Fulvudand (Pemehue) showed a decrease of this parameter, in spite of the non-significant change of bulk density. The stable structure of Andisols and their particle shape ensure that with only one wetting and drying cycle the precompression stress values are higher than those of Graneros soil, in spite of the lower values of bulk density. If we compare the effect of wetting and drying cycles on cohesion and angle of friction, the Coulomb failure line parameters for the investigated soils, a clear tendency was obtained only in the Graneros soil, as can be seen in Table 5.

Aggregate beds of the Osorno soil are not cohesive, the intercept of the Mohr-Coulomb line is negative. Six cycles of wetting and drying tend to decrease the non-cohesive condition, but are not enough to promote a positive cohesion. The Graneros soil, dominated by crystalline minerals, showed a tendency to increase the cohesion and decrease the angle of friction. Nevertheless, considering all the soils, only few treatments were statistically significant (values in bold). The 0-10 cm soil beds of Graneros soil have higher values of angle of friction than those of 40-60 cm, but the opposite is true for the Andisols. At both depths, the sequence of angle of friction is Osorno> Pemehue> Graneros.

The changes of mechanical parameters in Andisols are not directly related to the increase of bulk density values. The dependency between these parameters occurs only in the Graneros soil (Fig. 1).

In the Graneros soil, wetting and drying cycles promote an increase of bulk density, which results in higher values of precompression stress and cohesion. The percentage changes were positive and directly linearly related (Figs 1a and b), with higher increments on precompression stress values than on cohesion values. The bulk density dependency on mechanical parameters results in a good correlation between precompression stress and cohesion in Graneros soil (Fig. 1c). The behaviour of Andisols (Osorno and Pemehue) due to wetting and drying does not depend significantly on bulk density changes of the aggregate bed. One possible explanation is the presence of coarse porosity inside the aggregate, as could be assumed from mechanical parameters summed up in Tables 4 and 5. The other possibility is the effect of the pore water pressure changes that can act in different ways, depending on soil characteristics and the test conditions. Some results of the pore water pressure changes during mechanical tests are shown in Fig. 2.

Aggregate beds from 40-60 cm depth of Andisols are 'non sensitive' soils (Fig. 2a and c), especially in compression tests, if we consider the changes in pore water pressure values as the independent value. The low sensitivity can be derived from the mostly negligible small changes of pore water pressure when an external load is applied, because of the high water conductivity which allows fast water drainage during the compression test. The non-disturbed samples from 40-60 cm depth of Pemehue soil are very low sensitive too, while disturbed and undisturbed samples from the 0-10 cm layers of all the soils have important changes of

T a b l e 5. Cohesion (kPa) and angle of friction (°) dependence on wetting and drying cycles.

Soil	Aggregate size (mm)	No. cycles	0-10 cm depth			40-60 cm depth		
			Cohesion (kPa)	Angle of friction (°)	R*	Cohesion (kPa)	Angle of friction (°)	R*
Graneros (Haploxeroll)	<2	1	6.8	25.1	0.9999	**7.5**	**16.9**	0.9998
		6	10.2	19.4	0.9896	**9.3**	**13.6**	0.9995
	>2	1	0.0	34.9	0.9885	8.7	20.1	0.9998
		6	8.7	24.3	0.9930	10.4	19.1	0.9986
Osorno (Hapludand)	<2	1	-7.2	37.9	0.9938	-17.6	42.5	0.9981
		6	-2.1	35.5	0.9911	-13.7	39.6	0.9998
	>2	1	3.0	33.2	0.9933	-28.8	47.4	0.9995
		6	-5.9	38.6	0.9980	-25.5	46.6	0.9979
Pemehue (Fulvudand)	<2	1	**3.5**	**35.7**	0.9998	7.9	29.3	0.9999
		6	**6.6**	**28.8**	0.9999	5.9	31.0	0.9973
	>2	1	6.4	27.0	0.9943	1.7	35.7	0.9978
		6	3.7	34.0	0.9971	5.5	31.0	0.9966

*All values are significant ($P \leq 0.05$), values **in bold** are statistically different ($P \leq 0.1$).

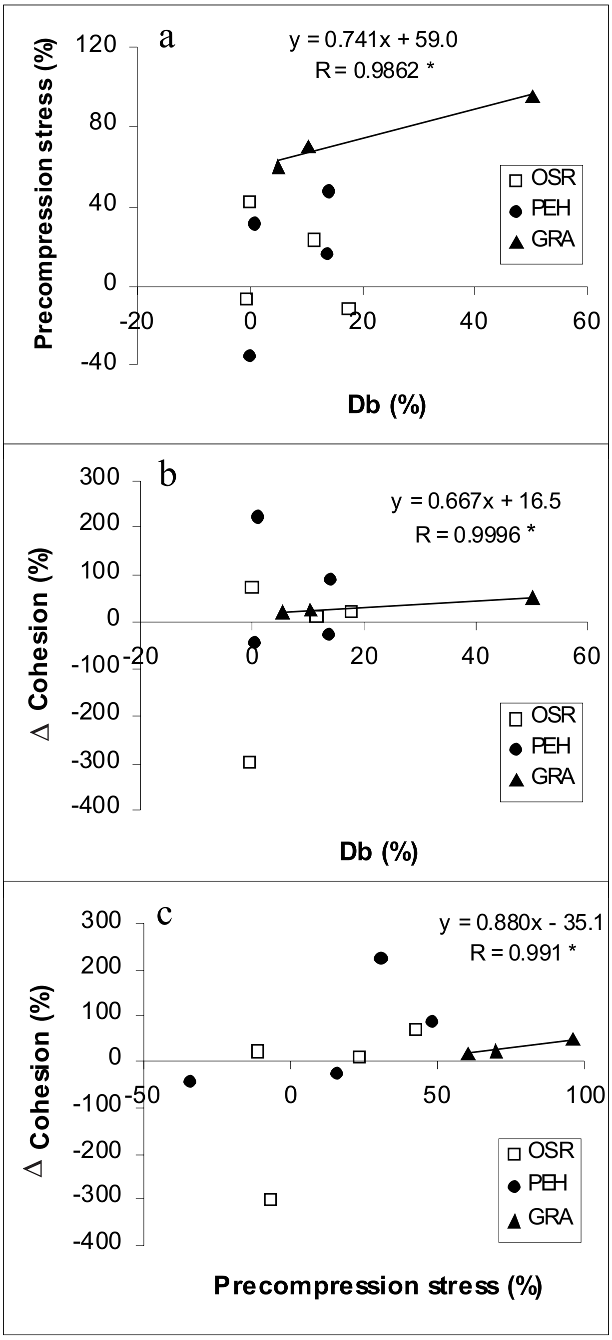

Fig. 1. Physical and mechanical properties (a, b, c) dependence comparing the change ( ) between one and six wetting and drying cycles on aggregate beds (* - significant with P≤0.05, OSR – Osorno soil, PEH - Pemehue soil, GRA - Graneros soil).

pore water pressure depending on the normal load applied. This condition could be related with the amount, size distribution and continuity of the pore system.

Aggregate beds from the two depths of Graneros soil and the 40-60 cm depth of Osorno soil showed higher changes of pore water pressure than beds coming from Pemehue, reaching even positive values when high normal loads were applied (300 to 400 kPa). Nevertheless, the high amount of inter-aggregate coarse porosity of aggregate beds allowed smaller changes of pore water pressure, compared with non-disturbed samples (data not shown).

The decreasing values of pore water pressure in Figs 2b and d are due to the shear during shearing test (for example, after 90 min for σ_1 = 300 kPa in Fig. 2b) or to the discharge process during the compression test (for example, after 70 min for σ_{1max} = 400 kPa in Fig. 2d). Some samples, especially at smaller normal loads, presented even a continuous decrease of pore water pressure during the entire test.

Considering a constant speed during test, in shearing tests (Figs 2a and b), between -60 hPa (at time 0) and maximum/minimum pore water pressure, it is possible to define an average rate of change, expressed as hPa min^{-1}, that depends on the normal load applied. The representative results for this behaviour are presented in Fig. 3.

Both curves are derived from Figs 2a and b and show good correlation between the rate of change of pore water pressure and the normal load applied. Graneros soil showed a decreasing positive slope. This denotes a maximum rate of change of pore water pressure, after which even positive values of water pressure generate neutral stresses that decrease the soil strength in shearing test or increase the precompression stress during compression test. In both Andisols, a linear tendency (constant slope) dominates when aggregate beds do not present the 'non sensitive' condition. In order to compare all the soils and treatments, a linear form is presented in Fig. 3b using the logarithm of the normal load (log kPa). The linear adjusts for all the treatments are presented in Table 6.

In general, wetting and drying cycles increase the rate of change of pore water pressure (slopes of adjusts, Table 6), because aggregates are rearranged and result in smaller (inter-) and most certainly intra-aggregate pores, which reduces the rapid drainage of the excess water if an external load is applied. The 40-60 cm samples from Pemehue soil have, on average, the lowest rate of changes, according with their non sensitive condition. This also explains the non-significant adjusts of coarse aggregate beds (2-6.3 mm). The superficial samples of Osorno soil have an erratic behaviour, it was impossible to obtain tendencies. Nevertheless, for the depth of 40-60 cm good correlations and the highest rate of changes were obtained.

In compression tests, the changes of pore water pressure of the non-sensitive aggregate beds could be explained as a linear adjust during the test (Fig. 2c). In fact, the low normal loads at the beginning of the compression test and their static nature allow that all treatments behave as very low sensitivity soils at the beginning of the tests, and after a critical load step, the pore water pressure increases (Fig. 2d). This behaviour can be represented by a bi-linear adjust, often used in the analysis of infiltration processes (Messing and Jarvis, 1993). Two examples of this behaviour are presented in Fig. 4.

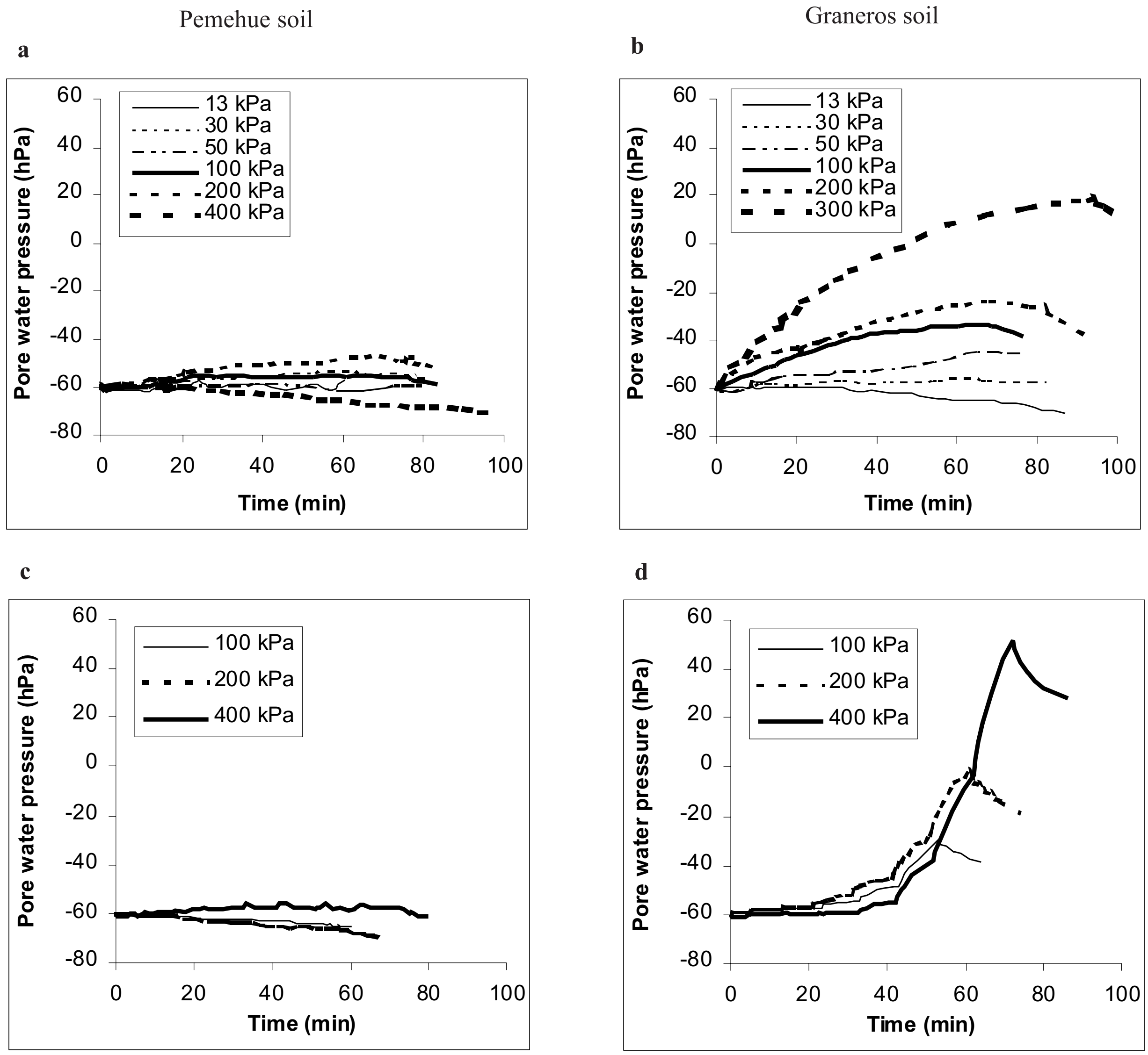

Fig. 2. Pore water pressure changes during mechanical tests at different maximum normal loads: 2-6.3 mm aggregate beds, 40-60 cm depth, all soils and treatments. a, b - shearing tests; c, d - compression tests.

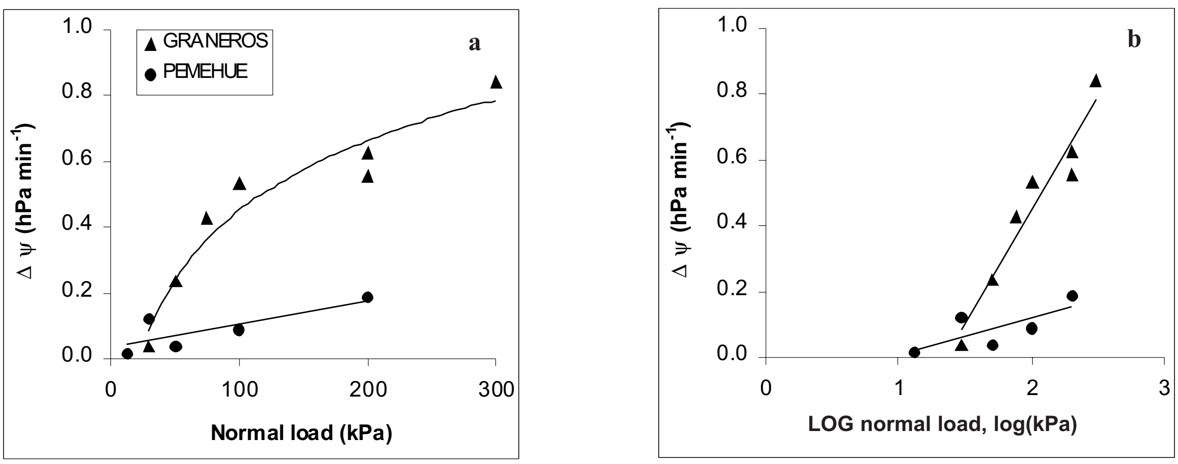

Fig. 3. Rate of change of pore water pressure ($\Delta\,\psi$) as a function of: normal loads during shearing (a), semilogarithmic plot (b).

T a b l e 6. Linear adjust of pore water pressure change rate as function of logarithm of normal load applied (x) during shear tests

Soil	Aggregate size (mm)	No. cycles	0-10 cm depth		40-60 cm depth	
			$\Delta\psi$ = Ax + B	R	$\Delta\psi$ = Ax + B	R
Graneros (Haploxeroll)	<2	1	0.363x + 0.0418	0.9673*	0.335x - 0.0608	0.4200ns
		6	0.465x - 0.0279	0.8699*	0.660x - 0.5834	0.7593*
	>2	1	0.465x + 0.1243	0.4898ns	0.480x - 0.4393	0.9326*
		6	0.745x - 0.6960	0.9342*	0.703x - 0.9536	0.9649*
Osorno (Hapludand)	<2	1	not determined		2.911x - 5.6225	0.9997*
		6	not determined		2.676x - 4.4590	0.9846*
	>2	1	not determined		3.445x - 6.7282	0.9594*
		6	not determined		5.497x -10.074	0.9062ns
Pemehue (Fulvudand)	<2	1	0.239x - 0.2820	0.5043ns	0.569x - 0.6398	0.8494*
		6	1.766x - 2.6494	0.9477*	0.215x - 0.2091	0.8160*
	>2	1	0.476x - 0.7655	0.7730*	0.046x - 0.1218	0.1265ns
		6	0.742x - 1.2013	0.8072*	0.109x - 0.0962	0.7384ns

*Significance ($P \leq 0.05$); A, B – parameters; $\Delta\psi$ – hPa min^{-1}; ns – not significant.

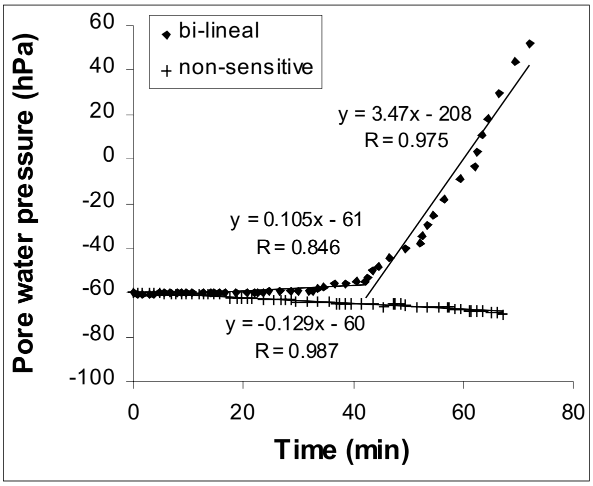

Fig. 4. Example of the uni- or bi-lineal adjust of pore water pressure as a function of time. The bi-lineal behaviour characterizes the critical external load, while the 'non sensitive' soil is independent of the magnitude of the external load.

Both samples presented in Fig. 4 and initially equilibrated at -60 hPa were consolidated at a maximum load step of 400 kPa. In the 'sensitive soil', the slope of pore water pressure increased after applying a critical normal load, in this case 100 kPa (minimum – 42), resulting the bi-linear adjust. On the other hand, in the 'non-sensitive soil', the tendency of the pore water pressure did not change, irrespective of the external load applied. The slopes of the adjusts and the critical normal load when the slope changed are shown in Fig. 4. Treatments with only one slope are 'non-sensitive' to the magnitude of normal load.

The results can be also explained by the pedogenetic processes. While all treatments of the more developed Graneros soil showed significant differences between the slopes 1 and 2 (this means that such soils are sensitive to external loads), practically all treatments of the youngest Pemehue soil are totally insensitive. The Osorno soil shows an intermediate situation. In Graneros soil, there is a significant increment of the rate of change of pore water pressure after applying the critical load, while these changes are more pronounced than those at 40-60 cm depth of Osorno soil.The critical load is maintained or increased after 6 cycles of wetting and drying. Thus, the soil strength is increased and only shows such tendencies at higher external loads. This strength regain is more effective in fine aggregate beds (0.63-2 mm). Moreover, in 0-10 cm samples of Graneros soil, the slopes are lower after 6 cycles, that is at similar range of external loads the rate of change of pore water pressure is lower, delaying the neutral stress formation. The 40-60 cm samples of Graneros and Osorno soils presented the inverse tendency, they became more sensitive to external load, increasing the slope (Slope 2, Table 7) after the application of the critical normal load.

The non-disturbed samples maintain the tendency associated with the evolution level, from the higher slope increments (slope 1 v/s slope 2) in Graneros soil, to the not or very low sensitive Pemehue soil.

T a b l e 7. Rate of change (hPa min^{-1}) of pore water pressure during consolidation tests. Uni- (Slope 1) or bi- (Slope 2) lineal equation based on Fig. 4

Soil	Aggregate size (mm)	No. cycles	0-10 cm depth			40-60 cm depth		
			Slope 1	Slope 2	Critical load (kPa)	Slope 1	Slope 2	Critical load (kPa)
Graneros (Haploxeroll)	<2	1	0.48	1.81 *	50	0.20	1.40*	70
		6	0.13	1.52 *	130	0.23	2.05*	100
	>2	1	0.53	2.80 *	70	0.17	1.50*	100
		6	0.19	1.17 *	80	0.16	2.28*	100
		Not disturbed	0.46	3.41 *	200	0.37	1.33*	200
Osorno (Hapludand)	<2	1	-0.26	0.09 *	30	-0.29	0.08*	30
		6	-0.19	0.09 ns	30	-0.07	0.66*	60
	>2	1	-0.35		-	-0.25	0.08*	70
		6	-0.23		-	-0.16	0.32*	70
		Not disturbed	0.14	0.33 *	150	0.13	0.52*	120
Pemehue (Fulvudand)	<2	1	-0.20		-	0.04		-
		6	0.41	1.55 ns	130	0.09		-
	>2	1	-0.11		-	-0.07		-
		6	-0.17		-	-0.05		-
		Not disturbed	1.35		-	-0.05	0.38*	300

*Statistically different values between slopes ($P \leq 0.05$), ns – not significant.

DISCUSSION

The mechanical properties of undisturbed soil samples are in agreement with other results of similar soils, considering the dynamics aspects of the tests (time interval between load steps and speed of shear). In this investigation, bearing capacity values are lower than similar matric tension conditions (Ellies, 1988) because a longer time interval results in a more complete soil settlement and in the avoidance of neutral stress formation. Cohesion values range between normal values of cattle sites from south of Chile. The lower cohesion and precompression stress of 0-10 cm from Graneros soil is due to the disruption of the structure at the soil surface and the compaction of the subsurface by the higher intensity of use (Ellies *et al.*, 2000). In Andisols the cohesion is higher in the surface horizon due to the effect of fine roots that increase the soil strength by drying, while the precompression stress and the angle of friction are nearly similar or increase with depth by the roughness and microaggregates characteristics depending on the volcanic glass material (Ellies and Funes, 1982).

Wetting and drying cycles promote the increase of bulk density in individual aggregates (Horn, 1993). For aggregate beds, the behaviour was similar on Graneros soil (Table 3) but not in all treatments of Andisols. Superficial samples of Osorno soil and coarse aggregate beds of Pemehue soil did not increase the bulk density, probably by a swelling effect when they were wetted. Higher amounts of organic carbon content in these treatments could have increased the swelling, explaining these results (data not shown). Another possibility is the suction-dependent hydrophobicity effect of organic matter that could prevent the normal wetting of the samples, which, however, after exceeding a certain suction range, may become less important (Orellana *et al.*, 2005).The wetting and drying cycles promote the increase of mechanical strength (Błażejczak *et al.*, 1995; Zhang *et al.*, 1997). This investigation maintained the tendency, but not always with significant differences. Superficial horizon of Graneros soil had an important increase of cohesion, but because of the variability of results no statistical differences could be determined. After six cycles, coarse aggregate beds of superficial horizon from Andisols became weaker. This result is expected for initially compacted soils or seedbeds of hardsetting soils (Barzegar *et al.*, 1995b; Bresson and Moran, 1995), but in this case there are a good structure and a bulk density in the normal range of Andisols. Assuming the aggregate hierarchy in Andisols (Seguel and Horn, 2005b), the decrease of cohesion in coarse aggregate beds of 0-10 cm horizon could be explained by densification of the aggregates during wetting and drying cycles. This implies that inside the aggregate there are coarse pores, and the contractile forces of the water menisci generated by the drying cycle pull the particles together inside the aggregate and not between them (Kemper and Rosenau, 1984). This process can be also derived from the precompression stress value, which decreased significantly in Pemehue soil.

The value of the angle of internal friction always decreased if the cohesion increased, associated with the higher contact area between particles or aggregates, as a result of the normal load applied, and the rearrangement and deformation of particles (Horn *et al.*, 2003; Pietola *et al.*, 2005). Comparing depths, the 0-10 cm aggregate beds of Andisols tend to have lower values of angle of friction than the 40-60 cm aggregate beds. This is explained by Ellies *et al.* (2000) as a consequence of particle shape of Andisols, irregular when soil material is fresh, but rounded by ploughing and soil evolution.

The changes of mechanical parameters are related with changes in bulk density values in Graneros soil only. The extrapolation of the adjusts of mechanical properties dependency on bulk density changes gives positive values when bulk density change is equal to zero. Under those conditions, wetting and drying cycles result in increased strength at the same bulk density.

In Andisols, the effect of wetting and drying processes on mechanical properties does not depend on the changes of bulk density of aggregate beds. The intrinsic properties that affect the mechanical behaviour of soil are the texture, kind of clay minerals, adsorbed cations, kind and amount of organic substances, bulk density and pore continuity. The higher the clay content and the organic matter content, the higher is the mechanical strength, depending on the arrangement, texture and mineralogy (Dalrymple and Jim, 1984; Barzegar *et al.*, 1995b; Zhang *et al.*, 1997, Shiel *et al.*, 1988, Witkowska-Walczak, 1981). The clay content is similar between the soils, and the amount of organic matter is not related with the results (data not shown). The randomly interstratified minerals of Andisols have higher strength than crystalline minerals (Barzegar *et al.*, 1995a), explaining the higher precompression values of Andisols than Graneros soil. Nevertheless, the complex interaction between mechanical and hydraulic stresses affect the changes of soil properties, defining structural, textural and pore water pressure effects while external loads are increasing (Horn, 2003; Pietola *et al.*, 2005).

During a mechanical test, initially the low normal loads decrease the diameter of the air filled inter-aggregate porosity (coarse pores), which promotes the redistribution of water to this new fine porosity, with the consequent decrease of pore water pressure. After that, for 'normal soils' (those with pore water pressure changes as a consequence of external loads), the pore water pressure increases by the dynamic nature of shearing test or by the higher normal load applied in the compression test. These external stresses compress the pores, affecting the continuity and the water fluxes (Horn, 2003). Assuming conditions near saturation, where the hydraulic conductivity tends to a maximum value for each treatment, the water fluxes should depend on the hydraulic gradient.

Nevertheless, the pore water pressure of some aggregate beds of Pemehue soil did not change significantly during the mechanical tests. For a 'non sensitive' soil (a soil in which the pore water pressure does not change significantly during mechanical stress, independently of the stress magnitude) this behaviour could be explained by a very abundant and strong pore system that maintains the pore continuity and results in fast drainage of excess water resulting in no changes in the pore water pressure. In other words, in this kind of soil, the gradient tends to remain constant because of very high hydraulic conductivity.

During shear tests, the rate of change of the pore water pressure depended on the magnitude of the normal load applied. There is a tendency to increase the pore water pressure changes as a result of wetting and drying processes. This means that the strength regain pulls together the particles or aggregates, decreasing the total porosity and the mean diameter. In other words, the soil becomes more sensitive to external loads. The positive intercept of superficial samples (0-10 cm) from Graneros soil when 1 cycle of wetting and drying was applied, at any aggregate size, denotes the instability of this soil: very low normal loads are enough to cause total collapse of the inter-aggregate porosity, which promotes the increase of pore water pressure. These results are supported by the lower values of precompression stress. The other treatments and soils presented a negative intercept, which means that the low normal loads decrease the diameter of the air filled inter-aggregate pore and that promotes the redistribution of water to this new fine porosity, with the consequent decrease of pore water pressure.

On compression test, the changes of pore water pressure are time dependent, and the changes during the test could be related or not related with the load magnitude, defining again sensitive and non- sensitive soils. The critical load was defined previously for different work conditions (Peng *et al.*, 2004; Seguel and Horn, 2005a). In aggregate beds, the high amount of pores in Andisols explains the negative slopes during all the tests, resulting in the absence of a critical load or, in other words, the presence of a non-sensitive soil. In non-disturbed samples of Pemehue soil, some replicates were non sensitive, but the tendency showed a constant increase of pore water pressure (0-10 cm) or a bi-linear behaviour (40-60 cm).

Nearing (1995) suggests that the effective stress depends on the saturation level of inter-aggregate porosity, and Ghezzehei and Or (2003) described a dynamic change of porosity system during a mechanical test, from open pores to closed pores, that resulted in overburden pressures. For our Pemehue soil, the results point to the presence of coarse porosity inside the aggregate, maintaining the continuity and functionality under high external stresses and preventing the neutral stresses. New investigations are necessary to describe this behaviour, in order to explain the role of pore water pressure in the effective stress theory and their relation with the soil evolution level.

CONCLUSIONS

1. The strength regain of soils, as a consequence of wetting and drying cycles, works in aggregate beds in similar way as in individual aggregates. In a crystalline clay soil, there is an increase in the mechanical parameters, associated with a bulk density increase. In soils derived from volcanic materials (Andisols with randomly interstratified minerals dominance) the results are not clear, and the increase of mechanical properties, as a consequence of wetting and drying cycles, would be prevented by the presence of coarse pores inside the aggregates. So, the drying cycle promotes the densification of the individual aggregates, resulting in a mellowing effect, with lower strength parameters of the matrix, especially in coarse aggregate beds.

2. The pore water pressure plays an important role in the transmission of effective stress, and its behaviour can be also linked to the soil genetic stage, associated with the coarse porosity. Comparing the studied soils, they were sorted from the most developed soil, with stress transmission by the liquid phase (neutral stress), to the youngest Andisol, with high amount of coarse pores which avoid that the pore water pressure changes significantly during mechanical test, independently of the magnitude of applied stresses. We call this soil a 'non-sensitive soil', and the behaviour would be explained by a high and very stable porosity inside the aggregate.

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